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APPENDIX I

ADVANCED TECHNOLOGY STUDIES
CITY OF TORONTO
DISTRICT HEATING AND COOLING

Prepared for

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APPENDIX I

Introduction

During the course of the Toronto District Heating and Cooling Study, MacViro Consultants were contracted by Energy, Mines and Resources Canada (EMR) - CANMET to evaluate technologies being investigated by others to reduce the capital investment and/or operating costs of district heating and cooling systems. These technologies include:

- ice slurries
- ice storage
- friction reducing additives
- increased velocities in distribution networks
- low temperature chilled water
- higher temperature differences

The work undertaken for EMR was done in conjunction with the broader scope of work undertaken by MacViro for the City of Toronto. Those aspects of the work that relate to the studies commissioned by EMR are presented in this Appendix, and in Chapter 8.0 and Chapter 12.0, Section 12.1.3 of the main report.

1.0 ICE SLURRY

A major portion of the capital cost of a district cooling system is associated with the distribution system. One method of reducing the cost of the distribution system is to reduce the pipe diameters while maintaining the capacity of the cooling fluid. This can be accomplished using ice slurries.

Ice slurry is a mixture of particle ice and water. When pumpable ice slurries are used as the medium for space cooling applications, a substantial increase in the "cool" carrying capacity of the distribution system results, compared to an equivalent circulating volume of conventional chilled water, due to the latent heat of fusion of ice. Chilled water, for example, can provide 29 mega joules per cubic meter of water for a typical operating temperature differential of 7°C (e.g., supply temperature at 6°C, return temperature at 13°C), while a 20% solids ice slurry can provide 66 mega joules per cubic meter, taking into account only the latent heat of fusion [Ref.1], or 120 mega joules if the ice slurry is returned at 13°C.

Ice slurry can be produced by several methods, only one of which is currently commercially available.

1. By a SUPER PAC heat pump. This method is based on the principle of super cooling water (water existing in the liquid phase below the freezing temperature is said to be super cooled). Water is super cooled in the evaporator of a heat pump and is fed into a reservoir. The contact (mechanical shock) of the jet of water with any part of the reservoir will normally result in water separating into solid and liquid fractions. This phase change occurs only in the storage reservoir where the ice separates from the water, forming a layer at the top of the reservoir [Ref. 2].

2. Direct contact slurry generation. These systems mix a refrigerant with water at a saturation pressure below that of the refrigerant to form ice particles which are then extracted in slurry form for pumping [Ref. 3].

3. Ice is formed in a slurry from brine or another binary solution in an agitated vessel in which the surface is cooled. This process is described in detail hereafter.

Sunwell Engineering Limited markets an ice slurry generator which produces a liquid crystalline solution by sub-cooling a binary solution of water and ethylene glycol or sodium chloride in the ice generator. The ice is prevented from forming on the cold surface of the vessel by agitation with a rotating wiper, which ensures mixing and a uniform temperature distribution throughout the solution. Ice fraction and crystal size in the slurry can be adjusted to suit the application by varying the residence time and flow rate in the ice generator unit.

From the ice generator, the slurry is pumped to a storage tank where the ice separates from the liquid, and the crystals form a porous layer on top of the liquid. The release of thermal energy stored as ice can be a one or two stage process. With the one stage process, liquid is pumped from the bottom of the tank to the building heat exchangers via the distribution piping system. The warm liquid from the heat exchangers is then returned back to the storage tank, entering via a uniform penetrating spray over the ice surface. As the returning liquid percolates down through the porous ice bed, the liquid is cooled down to the chilled water supply temperature and is recirculated back to the building heat exchangers. In the two stage process, ice crystals from the top of the storage tank are mixed with liquid to form a slurry of desired concentration. The ice slurry is then pumped to the heat exchangers where the ice is melted. The liquid returned from the heat exchangers is then introduced to the ice slurry tank to mix with the ice to maintain the ice slurry.

The one stage method can provide liquid at -1.1°C to 1.1°C (30°F to 34°F). The two stage process, depending on the binary solution concentration, typically provides ice slurry at tempertures from -2.2°C to 0°C (28°F to 32°F) [Refs. 4,5].

Studies conducted on the effects of ice particles on hydraulic drag in pipelines indicate that over a variable range of fluid velocity and ice fraction, ice particles seem to act as "flow straightening" additives which extend the region of sub-turbulent flow conditions to higher velocities. This effect may reduce pipe friction losses below those experienced with water alone, under similar hydraulic conditions. Friction factor values for 15% v/v suspensions of very coarse ice particles (mean diameter 1.2 cm) in water flowing through a horizontal pipe of 0.10 m diameter were found to be similar to those for solids-free water at velocities above 1 to 1.5 m/s. At lower velocities, frictional drag increased as a result of ice separation in the top half of the pipe cross section. For practical line diameters and operating velocities, ice solids concentrations up to 30% appear to have the same hydraulic behaviour as that of the carrier liquid at the same temperature and ethylene glycol concentration.

Storage of the slurry can be provided at either a central plant or at the user's building in a distributed storage system. Comparing the two arrangements, central thermal storage has the advantage of eliminating the tank storage space required at the user's building. Ice storage tank related costs are reduced due to construction economy of scale, and avoidance of operating and maintenance costs related to multiple tanks and controls. On the other hand, a distributed ice slurry storage system offers the potential of decreased distribution costs, responsive load management, and avoidance of potential ice plugging the distribution system branch connections.

Comparing the use of ice slurry against conventional chilled water for district cooling applications, ice slurry systems offer the advantage of smaller distribution pipes, circulating pumps and heat exchangers. These advantages are due to the additional cooling capacity of the circulating fluid. For example, a 300 mm chilled water distribution pipe, operating with a

temperature differential of 7°C (6°C to 13°C), can deliver up to 4070 kW (1160 R tons) of cooling at a velocity of 1.90 m/s. At the same velocity, a 20% slurry returning at 13°C could deliver the same amount of cooling using a 150 mm pipe and only 60% of the power is required for pumping chilled water via the 300 mm pipe. Similar downsizing is associated with the pumping and heat exchanger equipment.

Other potential benefits of ice slurry systems can be realized in new building design. With the ice slurry process, since the supply water is at or near the freezing point, less air volume is required to handle the building load, compared to conventional chilled water systems. Thus fans and fan motors can be smaller, reducing equipment and wiring costs. The diminished air volume also results in smaller ducts, potentially reducing the floor to floor height in multi-storey buildings allowing for additional savings. Further, as indicated in Chapter 8 of the City of Toronto District Heating/Cooling Study, the installed capacity of the chiller equipment serving an ice storage system can be reduced by 40 to 60% compared to conventional systems.

Ice slurry technology has the potential to offer reduced capital and operating costs in district cooling applications, however several problems have yet to be addressed. These include how to control the distribution of ice slurry and the associated plugging of lines in multi-branch distribution systems, and how to control the pipeline blockage associated with stopping and restarting some types of ice slurry.

Consultants to the Electric Power Research Institute stated that the melting temperature of ice, 0°C is lower than optimum for space cooling applications due to the increased condensation problems. However, if ice slurry was mixed with the return water when entering the building, the temperature could be maintained at the desirable levels. Also, such systems experience a reduction in efficiency and capacity of existing air conditioning chiller units when the evaporator temperatures fall below 5°C [Ref. 1].

The use of phase change materials to increase the energy carrying capacity of low temperature heat transfer fluids has been proposed to avoid some of the problems associated with water based ice slurry systems. Utilizing the latent heat associated with freezing/melting fluids having a freezing point of approximately 10°C would be considered ideal for space cooling applications [Ref. 6]. While this "warm ice" process is still under development, the use of storable and transportable ice slurries remains a promising technology due to the simplicity and low cost of plain ice.

2.0 FRICTION REDUCING ADDITIVES

Friction reducing additives (FRAs) are substances which suppress turbulence in fluid flow. The suppression of turbulence results in reduced frictional losses which translates into an increase in capacity of a given pipeline.

District heating and cooling (DHC) systems are typically characterized by extensive distribution piping systems which convey the pumped working fluid in the heating or cooling mode to residential, commercial and/or industrial buildings within a district. These systems operate with limited temperature differences, thus large quantities of fluids must be pumped. The operating cost associated with pumping the recirculating fluid is significant, as are the capital costs associated with the recirculation loop, pipes, fittings and pumps. The addition of small amounts of FRA's to the working fluid can reduce frictional losses in the system by as much as 80% compared to systems without additives. The result is an increase in the energy carrying capacity of the system and/or a reduction in the operating power costs, or for new systems, a reduction in the capital cost of pipes, fittings and pumps.

Additives that have the potential to reduce frictional losses in DHC systems can be divided into three groups:

1. High molecular weight linear polymers
2. Large aspect ratio fibres and filaments
3. Surfactants

Linear polymers include Polyox (polyethylene oxide) and Separan (polyacrylamide) which are effective at very low concentrations, however, their susceptibility to mechanical degradation, particularly under high temperature and high shear stress conditions, severely limits theirs usefulness in circulatory pipeline flow applications. Laboratory testing demonstrated that Polyox

reduced friction by over 60% at room temperature, however, it was completely ineffective at higher temperatures, and was found to be unsuitable for DHC applications as it degraded quickly and completely. Separan, for temperature's between 25 and 87.8°C, was found to reduce friction by over 60% accompanied by a corresponding reduction in heat transfer. Long term degradation tests with Separan resulted in minimum friction reduction of 6% at high temperature and 25% at room temperature. Additional tests need to be conducted with Separan to enhance friction reduction levels and to determine its applicability for district cooling applications.

Tests on Dacron and Nylon fibres have shown room temperature friction reduction of up to 19% and 50% respectively. Test results of heat transfer reduction or degradation for these fibres are not yet available.

Surfactants can be divided into three groups; anionic, non-ionic and cationic. Unlike high molecular weight linear polymers which degrade mechanically and irreversibly, surfactants are "repairable" in regions of moderate shear after they degrade under high shear conditions, such as those encountered in centrifugal pumps. Recent attention has focused in particular on the use of cationic surfactants which exhibit excellent drag reducing capability and long term durability.

Testing and screening of cationic surfactants as candidate FRAs for district heating applications have taken place for several temperature ranges. Complexes of quaternary ammonium chlorides with sodium salicylate were tested over a temperature range of 45 to 120°C, with the most promising being Kemamine Q-2983C and Kemamine Q-2803C. Friction reduction of up to 85% at temperatures up to 115°C were recorded, though a reduction in the heat transfer coefficient was noted in the temperature range where the additive was most effective at reducing friction. Degradation tests have yet to be conducted on these additives.

For the temperature range of 30 to 150°C, trimethyl ammonium-3-hydroxy-2-napthoate compounds were evaluated for friction and heat transfer reduction. These cationic surfactants

were Habon, Obon and Dobon. Habon was found to be effective for temperatures between 30 and 110°C. Obon for temperatures 50 to 130°C and Dobon for temperatures from 70 to 150°C. All three surfactants reduced friction up to 80% with a corresponding decrease in heat transfer reduction. While these additives are durable at temperatures less than 30°C additional testing is required to determine the applicability of these FRAs to district cooling systems.

Some studies have investigated the reduction in heat exchanger effectiveness associated with drag reduction when using FRAs. One study [Ref. 8] compared the factor for a tube-in-tube heat exchanger and a plate type heat exchanger. Using a surfactant FRA, it was observed that through a tube-in-tube heat exchanger the FRA reduced the hydraulic drag by 85 to 90%, however, the heat transfer was reduced by 90%. Tests of the plate heat exchanger showed a peak reduction in drag of 65% with heat transfer reduction ranging from 10 to 65%. One observation made regarding FRAs by the authors of this report is that with the decrease in turbulent flow leading to reduced friction, heat loss from the pipes also drops significantly.

Another study [Ref. 9] looked at the effects of a surfactant FRA on the performance of a shell-and-tube heat exchanger. The results showed that at low Reynolds numbers (i.e., low turbulence), the friction loss was reduced as was the heat transfer efficiency, however, operating at high Reynolds numbers the rate of heat transfer was increased considerably. The authors observe that with careful selection and operation of the heat exchanger systems, a system could be designed with low friction and heat losses in the distribution system and, at the same time, effective heat exchange at the user. This would provide another advantage as heat losses would be reduced in distribution systems.

Two projects that demonstrated the use of FRAs in operating district heating systems have been undertaken in Volklingen, Germany and Herning, Denmark.

The project in Denmark (1988/89) operated with the surfactant Habon, which proved to be a suitable additive for low temperature systems up to 100°C with a maximum temperature range of 50°C at concentrations less than 1000 ppm. Total drag reduction of approximately 80% in the system was recorded. Since the results were favourable the project was extended to 1991 with an improved additive.

In Volklingen, Germany, a demonstration project was begun in 1988 using the surfactant Dobon (160 - 115- ppm) which was effective for the temperature range of 90 to 140°C. Pressure drop reductions of up to 70% were recorded. A new additive mixed with counter-ions (Dobon - 6/sodium - salicylate) was tested in 1990, and was found to be suitable for a wider temperature range, 55-130°C, with drag reduced by approximately 60%. It should be noted that the drag reducing effect was lost in the middle temperature region from 60-80°C after a few days of operation in the system. This phenomenon was speculated to have been brought about by biological contamination from protein pieces produced in storage tanks. Storage tanks are open to the atmosphere for pressure compensation. The third phase of the project, which was started in the summer 1991, will last several years and will focus on changes in behaviour of the district heating system components, after which an economical analysis of FRAs should be possible.

Efforts to develop FRAs that are suitable for use in district cooling applications are in progress. One drag reducing agent developed, n-dodecyl trimethyl ammonium 2, 6-dihydoxy benzoate (n-DTMA 2, 6-DHB), provided 60% drag reduction at -2°C in ice slurries containing 10% by weight ethylene glycol. However, this FRA was found to be incompatible with the anionic polymer component of the initially recommended commercial corrosion inhibitor. The n-DTMA 2, 6-DHB drag reducing agent would be suitable for use in cooling systems that employ pure deionized, deaerated water with sodium hydroxide added for pH control, since interaction with corrosion inhibitors are eliminated.

The impact of FRAs on corrosion contamination and their interaction with other additives in district heating systems has been studied. Drag reducing surfactants have been shown to affect the corrosion characteristics of many commonly used piping and heat exchanger metals. Corrosion inhibitors, while decreasing the overall rate of corrosion of these metals, can also cause problems with respect to the susceptibility of the metals to localized pitting attack. Caution and understanding must therefore be utilized when considering the addition of either of these additives to a system.

Deionized, deaerated water was found to significantly reduce the rate of corrosion on metals commonly found in district heating systems and showed no susceptibility to localized corrosion (pitting) attack. Presently used commercial corrosion inhibitors, while reducing the corrosion rate even further, increased the risk of premature failure due to pitting.

Potential problem areas which need to be addressed in choosing corrosion inhibitor - FRA combinations for district heating applications include the effect of pH on critical pitting temperatures of metals in deionized deaerated water and stress corrosion cracking (cracking of a metal caused by the simultaneous presence of a tensile stress and a specific corrosive medium). Stress corrosion cracking is known to occur in copper based metal and amine-containing solution combinations and in stainless steel and chloride solutions. Chloride is contained in some FRAs while amine is contained in some corrosion inhibitors and some surfactants.

Water quality in district heating systems is often purified in a by-pass to prevent corrosion. The purification stages consist mainly of an ion exchanger to remove the water contaminants and a degassing stage to reduce the oxygen level. If surfactants are employed they must be separated before reaching the purification stage otherwise the ion exchanger will foul or the surfactant will be floated out in the degassing stage. The micellar phase can be separated by ultra filtration, which is a pressure driven membrane process, enabling the surfactants to be recycled after recovery.

In the event of an accident where large quantities of water are spilled, the surfactant may be deactivated by the addition of bentonite (a clay mineral) so that the surfactant is adsorbed and then flocculates. Only 50% of the counter ions are eliminated in this process. The bentonite/surfactant slurry can be separated, however the surfactant is not recoverable.

Surfactants can also be adsorbed by organic resins, which also separate any auxiliary counter-ions present. The resins can be recycled afterwards and the reuse of the surfactants is possible after further treatment.

In Canada, a research consortium has been formed led by EMR/CANMET. This group is part of a larger international effort through the International Energy Agency (IEA) to develop and explore applications of Advanced Fluids including FRAs.

Through work with Saint Mary's University, new low temperature additives have been developed for district cooling.

Analyses have shown that in larger pipes, say over 200 mm, design velocities cannot be increased due to concern about water hammer, etc. Therefore, benefits are chiefly for reduction of pumping energy. Smaller pipes may realize a benefit in pipe diameter reduction as well as pumping savings.

3.0 INCREASED VELOCITIES

Historically water distribution systems of all types (heating, cooling, potable water) are designed with velocities of 2 to 2.5 m/s. Selection of these velocities represents a compromise between the higher installed costs for larger diameter pipes versus the higher operating costs when velocities exceed 2.5 m/s. Interest is now being expressed in raising pipe velocities in some district heating applications to increase the amount of heat delivered by smaller piping systems. Some systems in Europe have installed transmission lines using velocities up to 3.6 m/s in piping of 1000 mm in diameter [Ref. 10]. As flow rate is directly proportional to velocity, an increase in velocity from 2 m/s to 3.5 m/s provides an increase of flow (hence heating system capacity) rate of 75% with the same piping system. For example, a 900 mm diameter pipe operating at 2 m/s and a $\triangle T$ of 40°C would deliver 760 GJ/h. Operating at 3.5 m/s, 1330 GJ/h could be delivered in the same diameter pipe. To put this in perspective, with this district heating/cooling study for the City of Toronto, the maximum heating load for the Railway Lands is 414 GJ/h. Cost savings in straightforward installation of pipes can be realized, and in restricted areas such as in tunnels alongside or under existing roads, where the size of pipe may affect the complexity of the installation, indirect cost savings may also be realized.

There are, however, drawbacks to using high velocities. From an installation point of view, larger pumps must be used and more complex measures are required to reduce the severity of hydraulic problems associated with thrust forces, cavitation and water hammer. Operating and maintaining a high velocity system also requires extra cost and effort. Piping erosion may be increased, maintenance efforts for a more complex system will be higher, and probably of most concern, energy costs will be higher.

In Table A-1, comparisons of the effect of different velocities are made for two flow rates. In the first case, three pipe sizes are selected at a flow rate of 0.15 m^3/sec to demonstrate the difference in power requirements between what would typically be considered as low, normal

and high velocity, respectively (1, 2 and 3 m/s). In the second case, two larger pipes are compared for normal and high velocities. It is clear that for both cases, with a change in velocity of up to 3 times, the resulting power requirements increase by 15 times.

Table A-2 was developed to show the economic differences between various scenarios. To simplify the analysis, in each case it was assumed that the installation consists of 1000 m of pipe, with two pumps (one duty, one standby). The capital cost was estimated and the annual periodic payment was calculated. The annual power costs were calculated using current Toronto Hydro costs for commercial power. Two scenarios were developed, one based on the system operating for 4 months of the year, the other 8 months of the year.

Table A-2 shows the sensitivity of the comparisons to the balance between energy cost and capital cost. When the system is used less often, energy costs drop and the capital cost dominates. When however the usage increases, the energy costs rise sufficiently to indicate that the normally accepted "medium" velocity is the preferred economic choice. Note that maintenance costs were not allowed for in these calculations. If included, the results would shift to favour the lower velocity system.

One method of reducing the impact of the higher friction losses, and hence power consumption, associated with the high velocity system would be the use of Friction Reducing Additives discussed in previous section of this Appendix. However, as empirical data on actual operating systems is limited, this report has not explored this option.

A potential application of higher velocities is in the design of distribution system for peak load hours. Often systems are conservatively designed to be able to service the peak hour load levels at the medium velocities. However, the system may only operate at that level for one or two days of the year. If piping systems were sized so that higher velocities were experienced during the peak hour period, the increased energy cost could well be considerably less than the capital

cost saving associated with the smaller diameter system. Note that in Table A-2 it was assumed that the systems were operating full time. If the high velocity case is used only for peaking (typical of a variable-volume distribution system), the increased power costs would reduce significantly and the cost saving of the higher velocities becomes more evident.

It is evident that in particular incidences the use of high velocities can provide a distinct advantage over "normal" velocities, however, each case must be carefully analyzed. When the cost of capital is high and the power costs are low the higher velocities appear to be favourable. When a system is run for a brief period of time at higher velocities and then run in the long term at conventional velocities, savings may also be realized. However, at this time the cost of capital is low (below 10%) and with Ontario Hydro predicting rate increases in excess of inflation, it appears that conservative energy designs will continue to be favoured.

4.0 CHILLED WATER DISTRIBUTION

Conventional district cooling systems typically deliver cooling water to customers at approximately 7°C, with return temperatures at approximately 13°C, resulting in a ΔT of 6°C. Space cooling at the individual customer buildings is accomplished by transferring heat within the building to the district cooling water circulation system, using various types of forced air-chilled water heat exchanger systems. Typically district chilled water circulation systems are directly connected to building system forced air cooling coils to avoid inefficiencies associated with intermediate water to water heat exchangers.

If intermediate shell and tube heat exchangers are utilized to isolate individual building systems from the district cooling recirculation system, the chillers are required to operate at lower supply and return temperatures, with lower efficiency results. Thus, such isolated systems are not common for district cooling.

One option to reduce the costs of district cooling systems is to lower the operating temperatures of the supply system, maintaining the same ΔT. For example, supplying chilled water at 0°C and returning from the buildings at 6°C. The effect of the lower operating temperatures is to substantially reduce the size of the cooling coils in the customer's building. This approach is compatible with the ice slurries or ice storage options being considered in this report, as the delivered temperature of these system would be at or near 0°C. For new buildings a cost saving can be realized with the reduction of cooling coil sizes in forced air systems while maintaining standard levels of air temperature in the distribution ducting. Alternatively, the forced air system could be operated at cooler levels and significant reduction could be realized in the sizing of the air handling system. In existing buildings the lower temperatures would increase the cooling capacity of the system.

The size reduction can be demonstrated by calculating the log mean temperature different (LMTD) for each of the temperature levels. In both cases the entering air temperature to a cooling coil is 26°C and the leaving temperature is 16°C. For standard water temperatures (i.e., 7°C/13°C) the LMTD is 10C° whereas with the lower temperature water (i.e., 0°C/6°C) the LMTD is 17C°. As the size of a cooling coil is inversely proportional to the LMTD, the size of the cooling coil for the lower temperatures would be 60 percent of the conventional coil.

Further to lowering the temperature, another option is to increase the water temperature change, with entering water at 0°C and leaving at 13°C. Compared to the conventional system a slight reduction in the cooling coil will be possible (LMTD = 14C°), however, the major cost saving will be associated with the smaller piping that could be utilized for distribution of the cooling water. As the change in temperature is essentially double, the equivalent capacity flow of the cooling water distribution system can be halved. This would not only reduce the capital cost of the system but would also reduce the operating costs as less pumping is required.

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